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ABSTRACT

Drawing parallels with critical thinking and creative thinking, this document describes some ways that scientific thinking is utilized. Cognitive approaches to scientific thinking are discussed, and it is argued that all science involves an attempt to construct a testable mental model of some aspect of reality. The role of mental models is portrayed with regard to problem solving and inferential thinking. Five major points are outlined that attempt to characterize scientific thinking in light of the "mental model" approach to science. These state that: (1) mental models are constructed representations of the perceptual world; (2) mental models can be verbal, visual, or mathematical in nature (or some combination of the three); (3) mental models are based on existing scripts and schemata in the knowledge base; (4) inferential extensions are not based on formal processes; and (5) seeking new data is done in ways that depend on the nature of the current mental model. Implications of this view of scientific thinking on education are disucssed, and the five points are used to evaluate a biology textbook and a physics textbook. (TW)

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What Is Scientific Thinking?

by

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WHAT IS SCIENTIFIC THINKING?

My title presupposes something, namely, that I will answer the question by providing a definition of scientific thinking. In fact, however, I propose not to answer the question, and my reason for refusing to do so is the main point that I will argue in this paper. Let me explain by reference to two famous precedents, Charles Darwin's Origin of Species (1859) and Isaac Newton's Principia Mathematica (1687). Neither is a "mushy" book in any sense of the word, yet neither defines its subject matter.

Consider Darwin first. He begins by providing the reader with an analogical basis for his main argument about natural selection. Chapter 1 deals with "artifical" selection, pigeon-breeding and such, as a way of convincing the reader of the possibility of selective effects on a broader scale. Chapter 2 then considers previous definitions of the term "species," and rejects all of them for one reason or another. No better definition is offered -- in fact, darwin refuses to define the term. "Species," "Varieties," it's all the same to him. What counts is the fact of variation in general, not a set of arbitrary dividing lines between one type of animal or plant and another. The rest of the book justifies his approach. Darwin does not tell us what species are, he tells us how they change.

Newton's Principia similarly avoids definition. "Matter" is not defined, nor is "Force." Instead, Newton begins with a set of "definitions" (his word, not mine) that tell us how to measure mass and momentum. He derives several ways to compare the proportional amounts of different forces. Then it's on to his discussion of absolute vs. relative space, time, and motion, after which we get the three laws and a lot of mathematics. "I do not define time, space, place, and motion, as being well known to all" (Newton, Cajori translation, p. 6). Again, Newton does not tell us what forces, etc. are, he tells us how they work.

Thus cloaked in precedent, I propose not to tell you what scientific thinking is, but a few things about how it works instead. Much the same should be done (I think) with critical and creative thinking. We can say a lot now about how all three kinds of thinking work, but we will lose the heuristic value of the enterprise if we stop to worry about how each is to be defined. The ploy worked for Darwin and Newton, it can work for us.

In the rest of this paper, I'll try to say a few things about how scientific thinking works, concentrating on those aspects that have the most apparent relevance to education. Then I'll draw out some of the implications for education, being as speculative as possible.

1. Cognitive Approaches to Scientific Thinking.

One feature seems common to most kinds of science, namely, that all science involves an attempt to construct a testable mental model of some aspect of reality. Mental models have played a large role in cognitive science in the last ten or so years, and there is a lot to draw on. They seem to be involved in most kinds of problem solving tasks and in most kinds of inferential (and even deductive) reasoning. What distinguishes scientific thinking, however, is the focus on testability, which makes science different from most other kinds of thinking. Artists use mental models too, but they don't worry about testability (at least not in the same sense). Testability can mean "potential disconfirmability," but psychologically, even for highly sophisticated scientists, it is more closely approximated by a kind of pattern-matching process. The scientist shouts "Eureka" only when the mental model fits with something more directly perceptual and less directly mental. No one shouts "Eureka" when the data disconfirm the prediction (unless somebody else's mental model is being disconfirmed!). Eureka experiences are, in short, based on pattern-matching, on in the fit between the scientist's construal of the phenomenon and the phenomenon itself. And a "construal" is what we mean by the term mental model. It's possible now to see why avoiding definitions as Darwin and Newton did is so powerful a heuristic. What definitions do is freeze a mental model; they are quite appropriate when the goal is unchanging mental models. But if the model is imperfect, or if the state of knowledge is less than complete, they serve only to rigidify the process, working against further change. Loosely held ideas are the most flexible and hence the most adaptable.

With thi as my basic characterization of science, I've outlined five major points which highlight what I see as defensible generalizations about how scientific thinking works. Each can be supported by recent cognitive research (see Tweney, Doherty, & Mynatt, 1981 and Tweney & Walker, forthcoming, for a detailed literature survey):

1. Mental models are constructed representations of the world which are isomorphic to at least some aspects of the perceptual world. The properties of any one such model place boundaries upon (determine?) the kind of thinking which occurs and the kinds of strategies which are likely to prove useful. Under ordinary conditions, only one such model can be considered at one time. Otherwise, "overload" occurs.

2. Mental models can be verbal/propositional in nature, mathematical in nature, visual in nature, or some combination of the three. To some extent, verbal and visual models can coexist without overwhelming processing capacity, thus overcoming to some extent the constraint noted in point 1 above. It is not known if mathematical models buy the same advantage, though presumably they do.

3. Mental models are based on existing scripts and schemata in the knowledge base. Reciprocal processes of assimilation and accomodation occur, and these seem to be the basis of changes in the scripts and schemata. Knowledge bases develop over time, getting larger, richer, and more automated, provided that large amounts of experience utilizing the knowledge base occur. Otherwise, the Ebbinghaus forgetting curve applies. Note that a mental model is not the same thing as a knowledge base.

4. Inferential extensions ("going beyond the data given") are not based on formal processes of logical reasoning, but rely instead on informal reasoning processes such as analogy, metaphor, imagery, etc.

5. When people seek new data, they do so in ways that depend on (and are limited by) the nature of the current mental model, as well as long-term purposes and goals. Information-seeking is governed by high level heuristics which sometimes work against testability in the formal sense (a "confirmation heuristic") and sometimes resemble formal logical processes (a "disconfirmation heuristic"). More often they are adaptive mechanisms for dealing with imperfect data and imperfect theories.

You can find cognitive psychologists who would quibble with one or another aspect of my list, to be sure, but I think all are defensible in the sense that all have been shown to hold not just for laboratory tasks but for at least some instances of "real-world" science as well. The list is also incomplete, but then my paper is short. In any case, what does this have to do with education?

2. Implications for Education.

Let me approach this problem by focussing on textbooks in science education. I've chosen two books to focus on, Peter Jensch's Biology, The Science of Life (Houghton Mifflin, 1980) and John E. Willams, et al, Modern Physics (Holt, 1984). Each is an excellent book in many ways, but I am going to look at them from the special standpoint of the properties of scientific thinking as I have outlined them. Do they conform? The answer is pretty clear -- no, they don't.

Let's start with my point about definitions. Both texts fail badly in this regard. Jensch asserts that vocabulary is minimized in favor of explanation and understanding, yet the book's chapter-end vocabulary lists define 425 items in 17 chapters. Williams gives 636 definitions in 25 chapters. Both books are very careful to "define their terms" in just the sense I suggested Darwin and Newton avoided, and with a consequent loss in heuristic flexibility. A few years ago I sat through a first year college French course. As I recall, the target vocabulary was about 1000 words during the year, making our high school science courses not all that different from a college foreign-language course in the amount of vocabulary we expect from

students. Is this what science is really all about?

Do we really want to freeze so much conceptual material in the minds of our students? What happens to the capacity to modify one's mental models if we do so?

How about the five points in the list above? How do the texts measure up in this regard? Results are a bit more mixed, as the following list suggests:

1. Mental Models;

Jensch
Constructive nature of mental models not stressed. Most given as "real." Tie to perceptual experience only sporadically emphasized. "Overload" caused by multiple models not stressed.

Williams
As Jensch, but less tie to perceptual experience.

2. Verbal/Visual/Mathematical Aspects of Mental Models;

Jensch
Mathematical representations not used. Some excellent verbal/visual correlations.

Williams
Lots of math, sometimes correlated with visual or verbal representations, sometimes not. Good use of three-dimensional figures.

3. Relation to Knowledge Base;

Jensch
Sporadic use of prior knowledge of student. Tendency to introduce "exotics" as examples. Fairly accumulative in organization. Little repetition of basic concepts.

Williams
Very little use of prior knowledge of student, but rigorously accumulative in organization. Little repetition of basic concepts.

4. Inferential Extensions are not Formal;

Jensch
Chapter 1 is o.k. on this. Good discussion of the unprovability, in the logicl sense, of scientific generalizations. Rest of text has a different message, implying that formal logical "truth" is the heart of biology.

Williams
Chapter 1 o.k. Rest of text gives a different message, implying that formal logical, and especially mathematical,

development is the heart of science.

5. Information-seeking Heuristics;

Jensch
Chapter 1 is reasonable in describing these, rest of text creates a different impression.
Williams
As for Jensch.

A text book obviously is not all there is to science education; in that sense I am picking on them unfairly. Yet in a larger sense, I think we must ask what the function of the text ought to be if it is not providing an accurate picture of how scientists think. And if we aren't showing them how science works, can we really expect them to become scientifically literate in the sense needed for today's world? Here, a cognitive view can be enormously useful. Why not show them the reality of science? Why not teach science in a way that ties the abstract concepts to the perceptual reality of the student? Why not reveal the secret, that scientists, like artists, create a world but, unlike artists, constantly test that world? Why not acknowledge that scientific thinking and critical thinking and creative thinking are not different dimensions but different aspects of the same thing?